Monitoring of Streambank Erosion Processes: Hydraulic, Hydrologic and Geotechnical Controls

Andrew Simon[1] and Natasha Pollen[2]

[1] USDA-ARS, National Sedimentation Laboratory

[2] Department of Geography, Kings College, London

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How Much Sediment Comes from Bank Failures?

- Widening rates of up to 100 m/yr
- Up to 90% of the sediment emanating from eroding channels
- Often, more than 50% of the sediment emanating from a watershed
- One 1.0-m failure along a 5-m high bank along a 100-m reach = 400 tonnes or about 26 dump trucks

Little Blue River, Kansas

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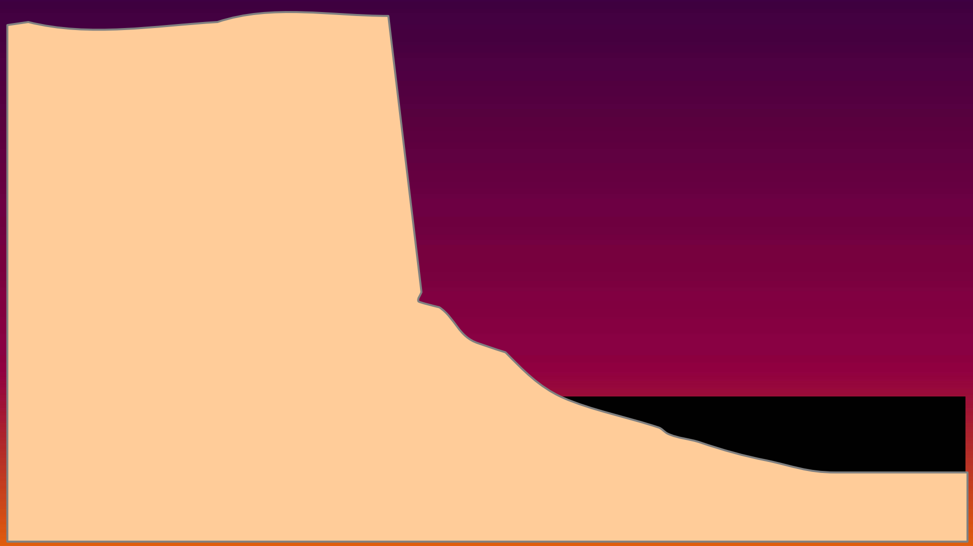
Bank Retreat Processes



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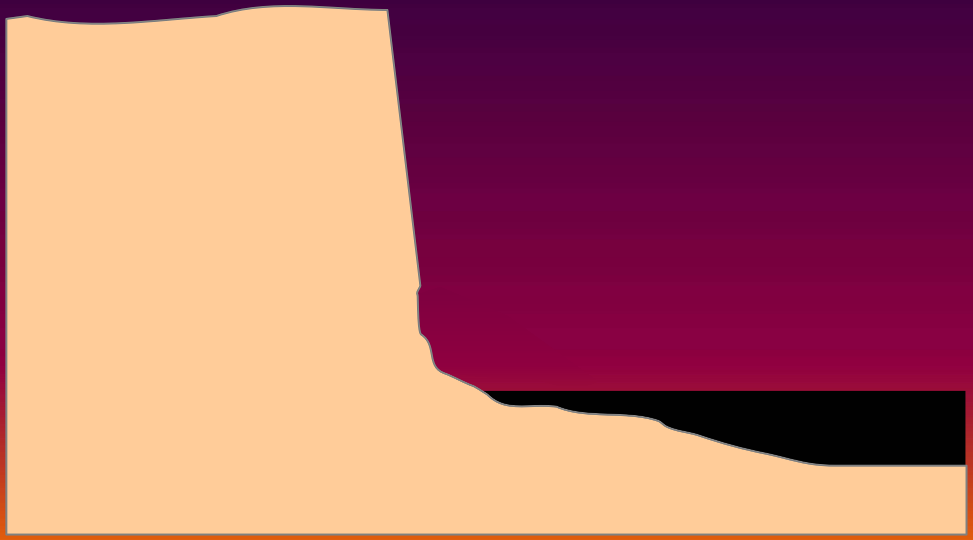
Bank Retreat Processes

Toe erosion
steepens bank

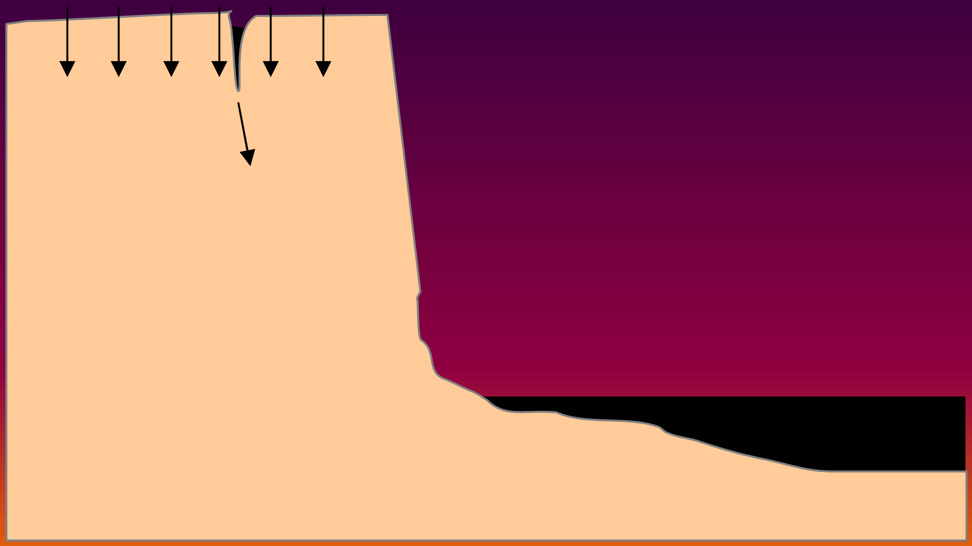


Bank Retreat Processes

Tension crack
develops

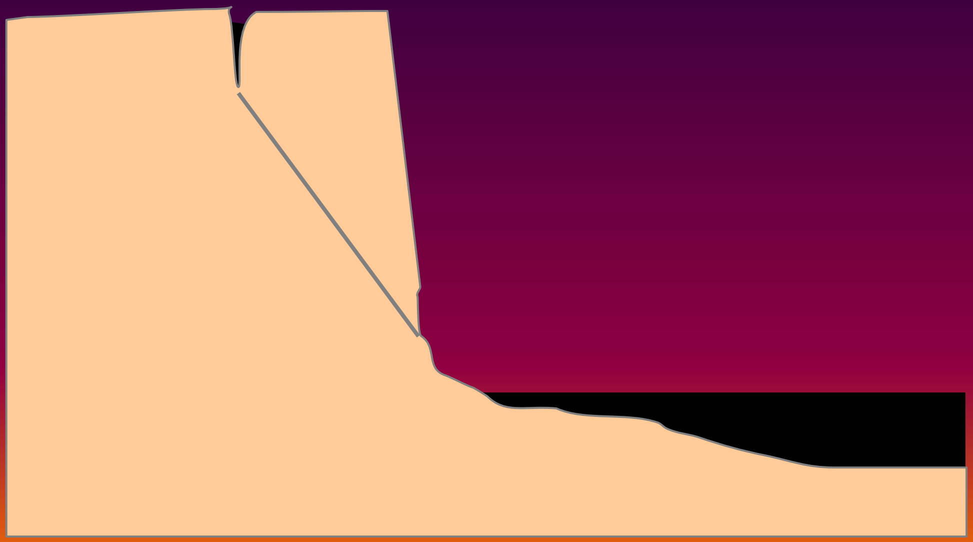
Bank Retreat Processes

Infiltration raises pore-water pressure



Bank Retreat Processes

Shearing starts



Bank Retreat Processes

Bank failure
occurs

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Bank Retreat Processes

Erosion removes
the failed debris

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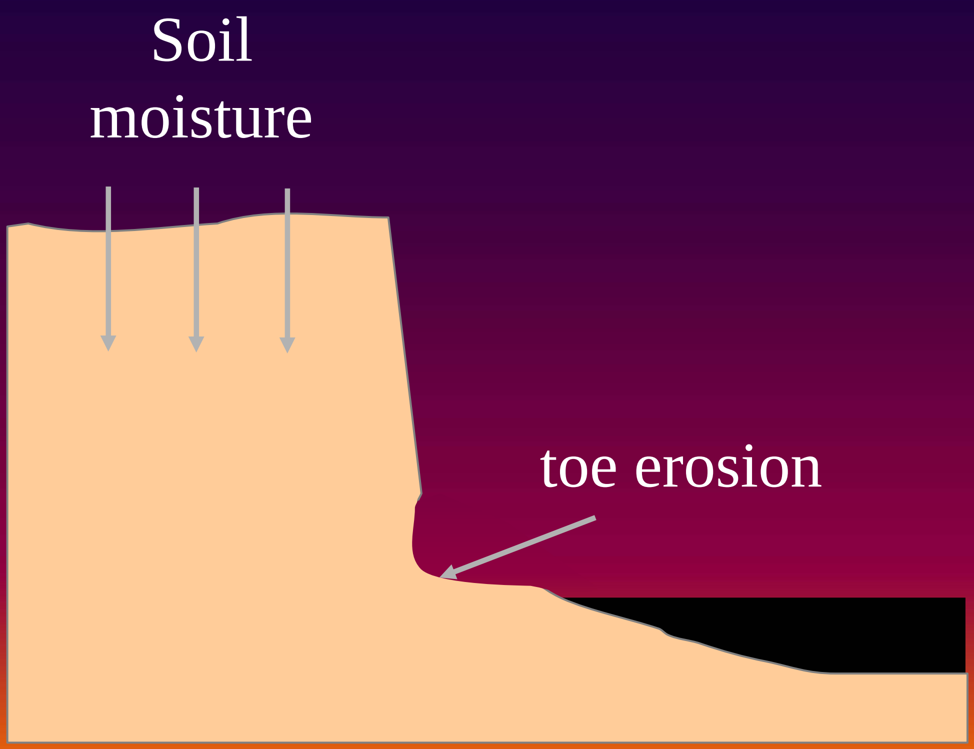
Bank Retreat Processes

Bank steepening
starts again

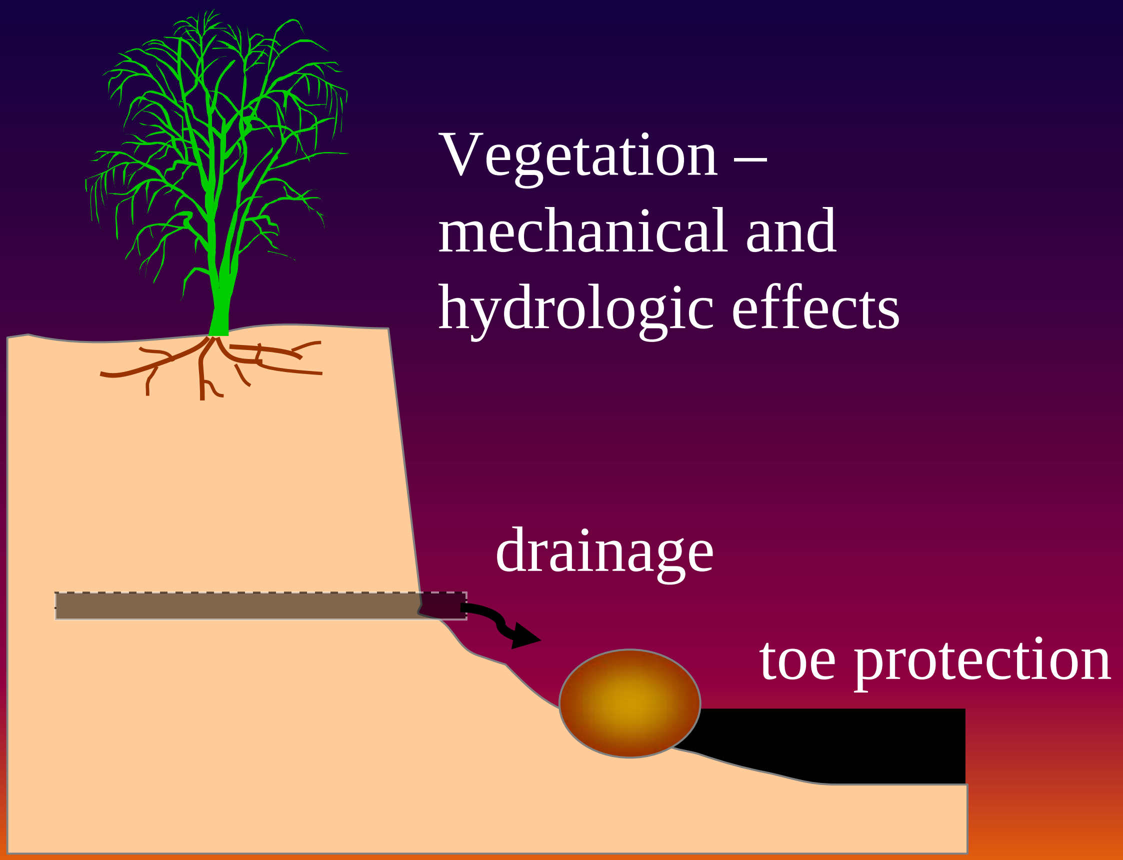
Bank Retreat Processes

Vertical face

Bank stability is decreased by….



Bank stability is increased by….



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Fundamental Processes Behind Bank Stability

If we want to predict bank stability we need to quantify the underlying processes. These are:

- **Bank shear strength** (resistance to bank failure)
- **Bank toe erodibility** (resistance to toe erosion)

Bank Stability – The Factor of Safety

$$\text{Factor of Safety } (F_s) = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

If F_s is greater than 1, bank is stable. If F_s is less than 1 bank will fail. (We usually add a safety margin – $F_s>1.3$ is stable.)

Resisting Forces	Driving Forces
soil strength	bank angle
vegetation	weight of bank
matric suction	water in bank

Strength of Soil Materials

- **Effective cohesion** (high in clays, moderate in silts, absent in sands and gravels)
- **Friction** (high in sands and gravels, low in clays)
- **Pore-water pressure** – the most dynamic variable

$$\tau_f = c' + (\sigma - \mu_w) \tan \phi'$$

where

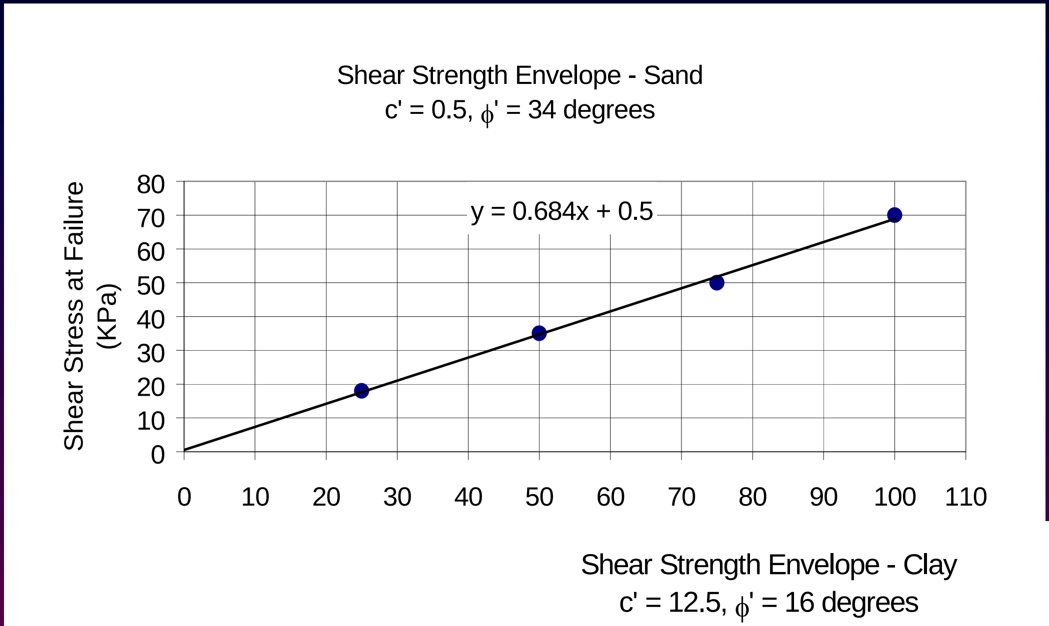
τ_f = shear strength (kPa); c' = effective cohesion (kPa); σ = normal load (kPa); μ_w = pore-water pressure (kPa) and ϕ' = effective friction angle (degrees).

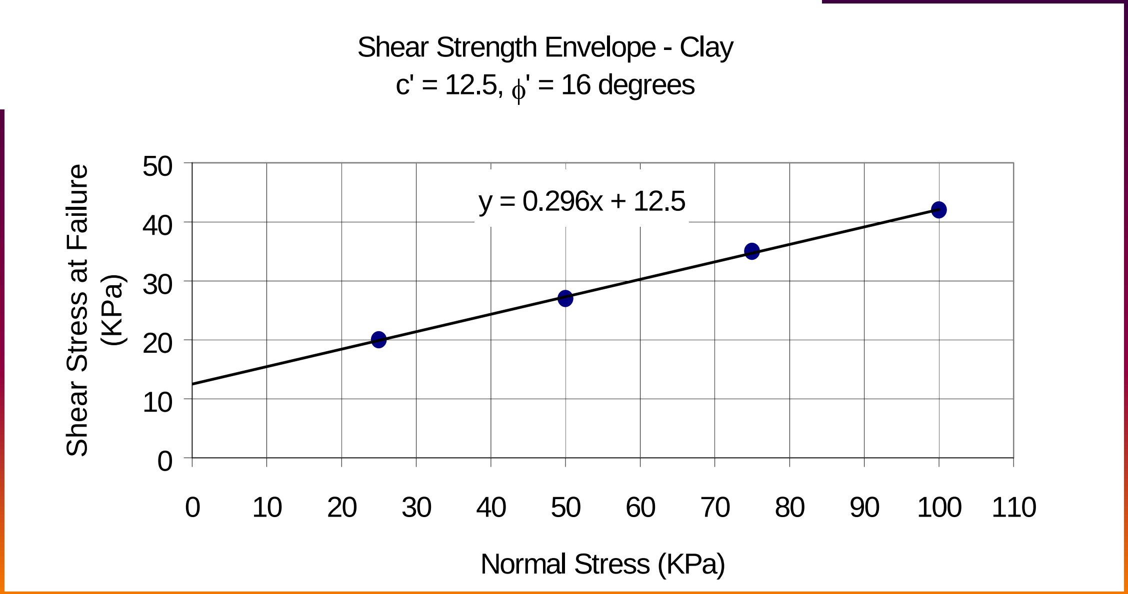
Measuring Soil Strength

- **In-situ tests** – Borehole shear test (BST)
- **Torvane shear** (combines cohesion and frictional strengths)
- **Laboratory test** – shear box and triaxial cell

Advantages and Disadvantages

Soil-Strength Testing





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Effects of Pore-Water Pressure

- Pore-water pressure reduces effective friction – weakens the soil
- Increases weight of bank
- However, negative pore-water pressure (matric suction) increases bank strength
- Converting positive to negative pressure (lowering water table) increases strength

Measuring Pore-Water Pressure

- Measure directly using tensiometers and piezometers
- Infer from water table height

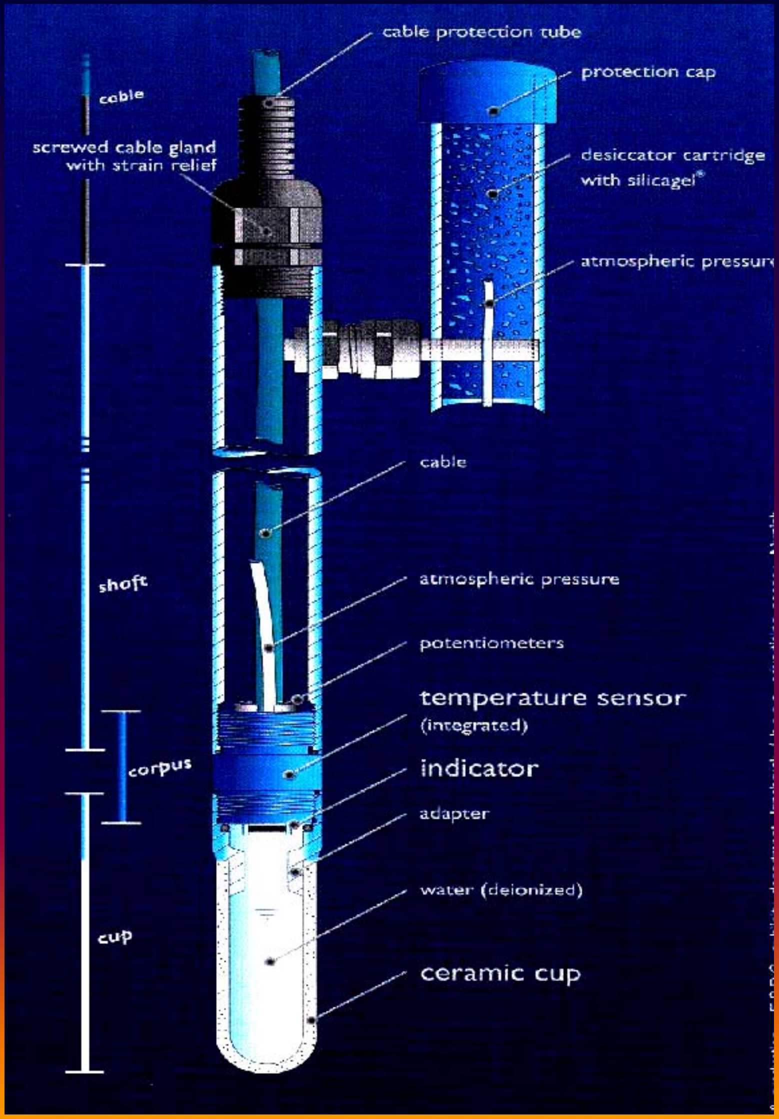
$$\mu_w = h\,\gamma_w$$

where

μ_w = pore water pressure (kPa);

h = head of water (m);

γ_w = unit weight water (kN/m^3)

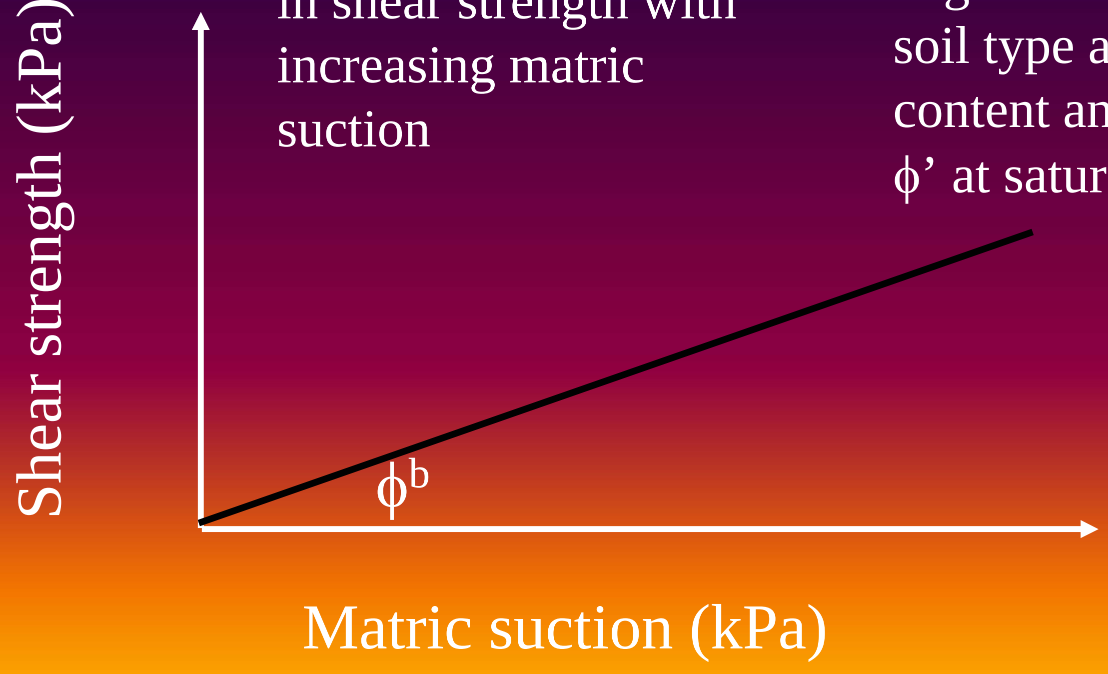


Converting Matric Suction to Apparent Cohesion

- Negative pore-water pressure does not directly translate to added cohesion

ϕ^b is the rate of increase in shear strength with increasing matric suction

ϕ^b ranges from 0 to 20 degrees depending on soil type and moisture content and is equal to ϕ' at saturation



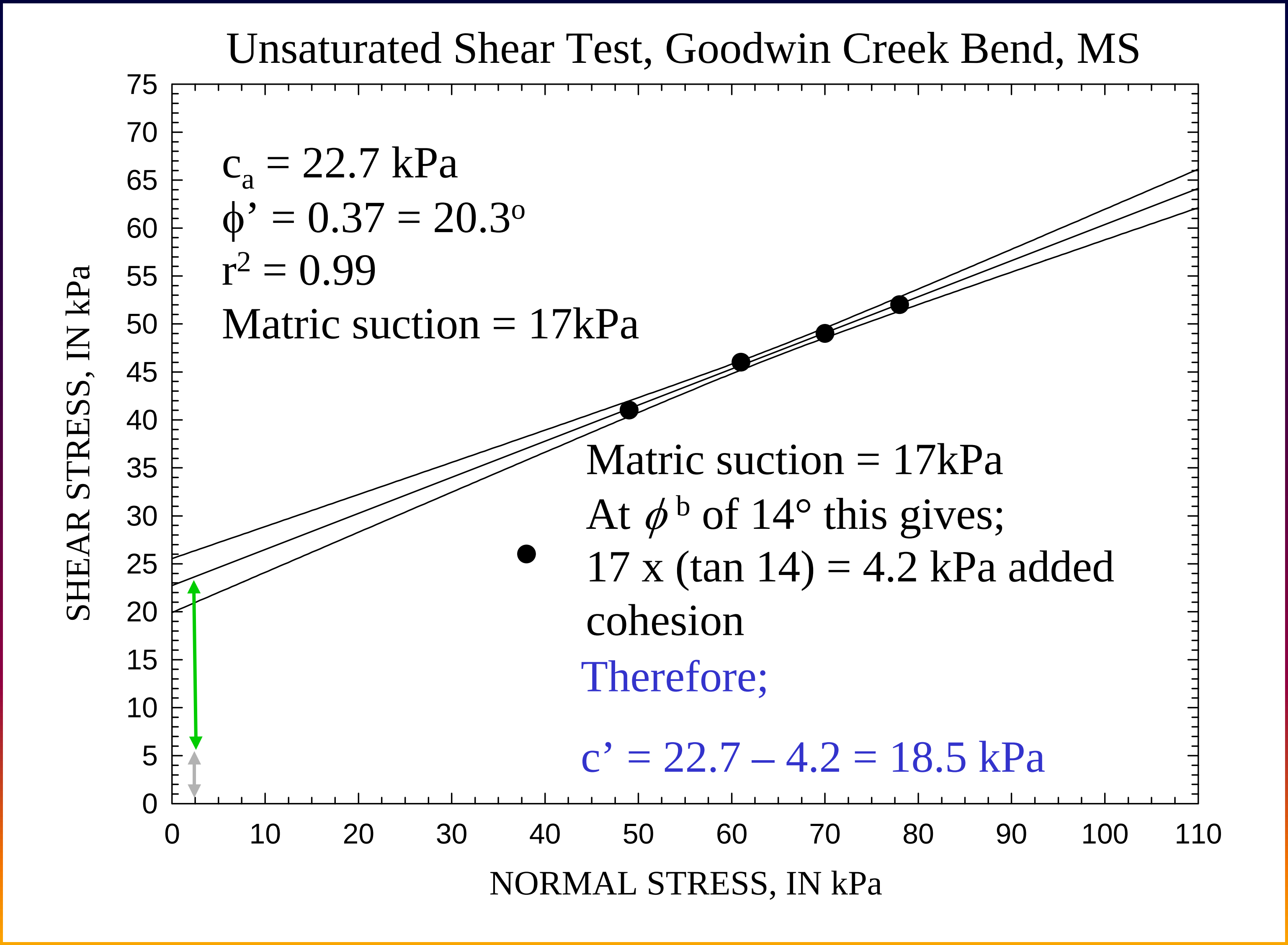
Incorporating Matric Suction as Apparent (total) Cohesion

$$c_a = c' + (\mu_a - \mu_w) \tan \phi^b$$

Where:

c_a	=	apparent (total) cohesion
c'	=	effective cohesion
$(\mu_a - \mu_w)$	=	suction on the failure plane
ϕ^b	=	angle representing the relation between the shear strength and matric suction

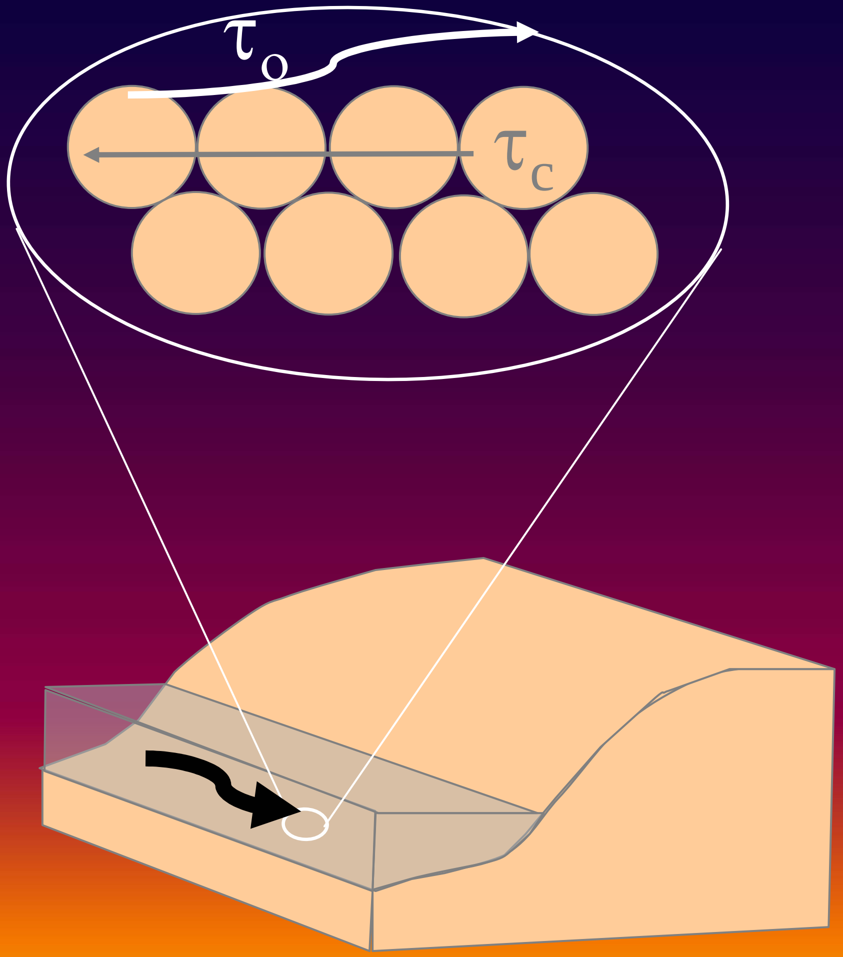
Incorporating Suction in a Strength Test



Hydraulic Erosion Processes

Flowing water exerts a shear stress on the toe and bank; τ_o is a function of water surface slope, hydraulic radius and unit weight.

Bed and bank material have resistance due to friction, cohesion and weight. A certain amount of shear stress, is required to overcome this (critical shear stress; τ_c).



Boundary Shear Stress

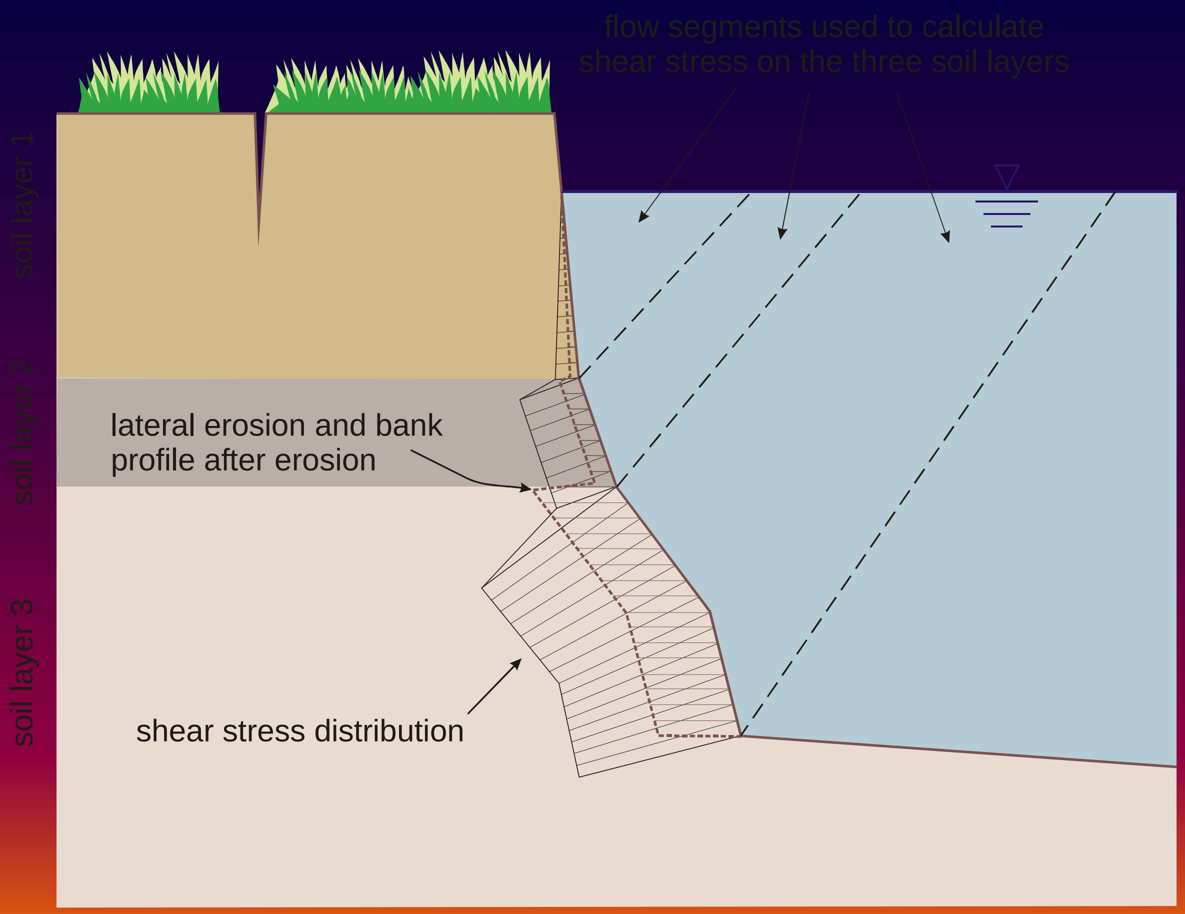
- **Average shear stress τ_i on each soil layer**

$$\tau_i = \gamma R_i S_f$$

$$R_i = A_i / P_i$$

- **Average erosion distance ΔW_i**

$$\Delta W_i = K_i \left(\tau_i - \tau_{c,i} \right) \Delta t$$



Erosion Rate is a Function of Erodibility and Excess Shear Stress

$$\varepsilon = k\,(\tau_o - \tau_c)$$

ε = erosion rate (m/s)

k = erodibility coefficient (m^3/N-s)

τ_o = boundary shear stress (Pa)

τ_c = critical shear stress (Pa)

$(\tau_o - \tau_c)$ = excess shear stress

Obtained from jet-test device

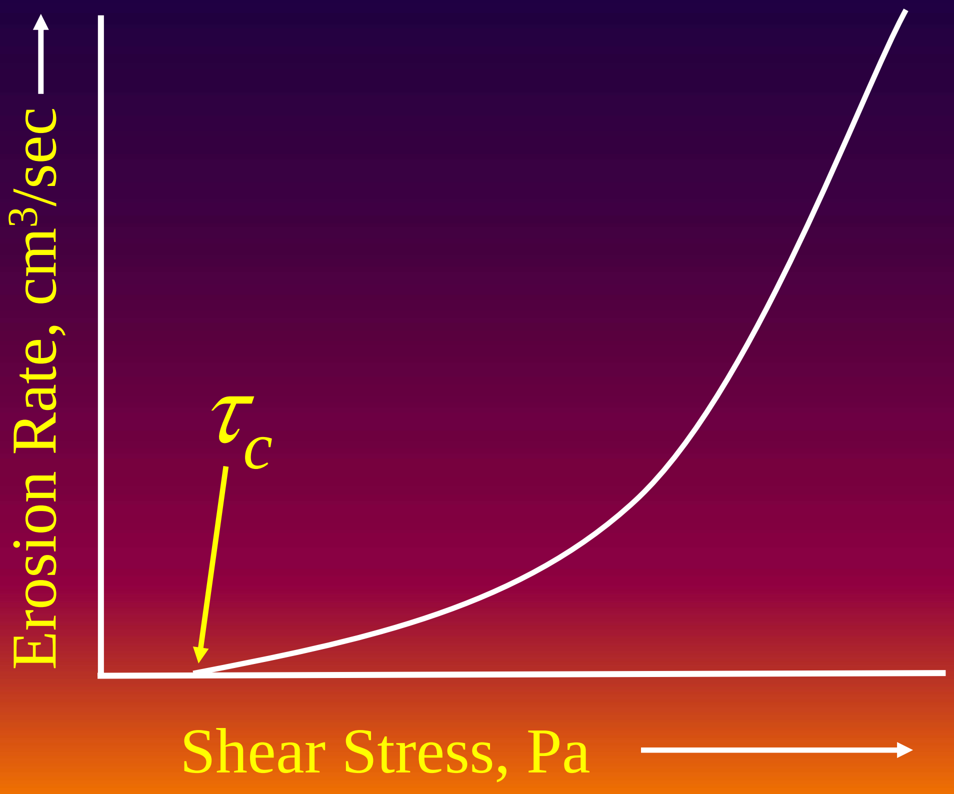
Critical shear stress is the stress required to initiate erosion.

Measuring Bank and Toe Erosion Threshold and Erodibility

- Jet-test device scours a hole in the bank or toe and measures the shear stress and erosion rate
- From this we calculate critical (threshold) shear stress and erodibility coefficient, *k*

Measuring bank erodibility with the non-vertical jet test device

From Relation between Shear Stress and Erosion We Can Calculate τ_c and ε



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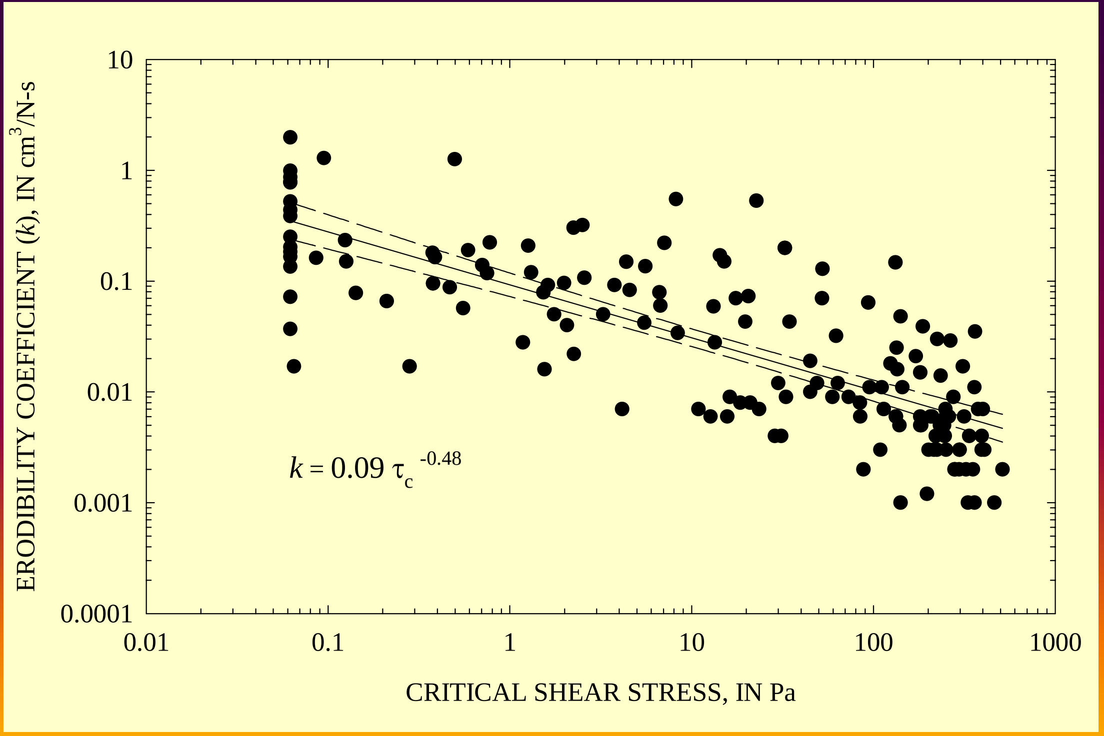
Erodibility

Erodibility, m^3/N-s

$$k = x\,\tau_c^{\,y} = 0.1\,\tau_c^{\,-0.5}$$

Where; τ_c = critical shear stress (Pa),
x, y = empirical constants



Effects of Vegetation on Bank Stability

	Mechanical	Hydrologic
Stabilizing Effects	* Increased strength due to roots	* Canopy interception * Transpiration
Destabilizing Effects	* Surcharge	* Increased infiltration rate and capacity

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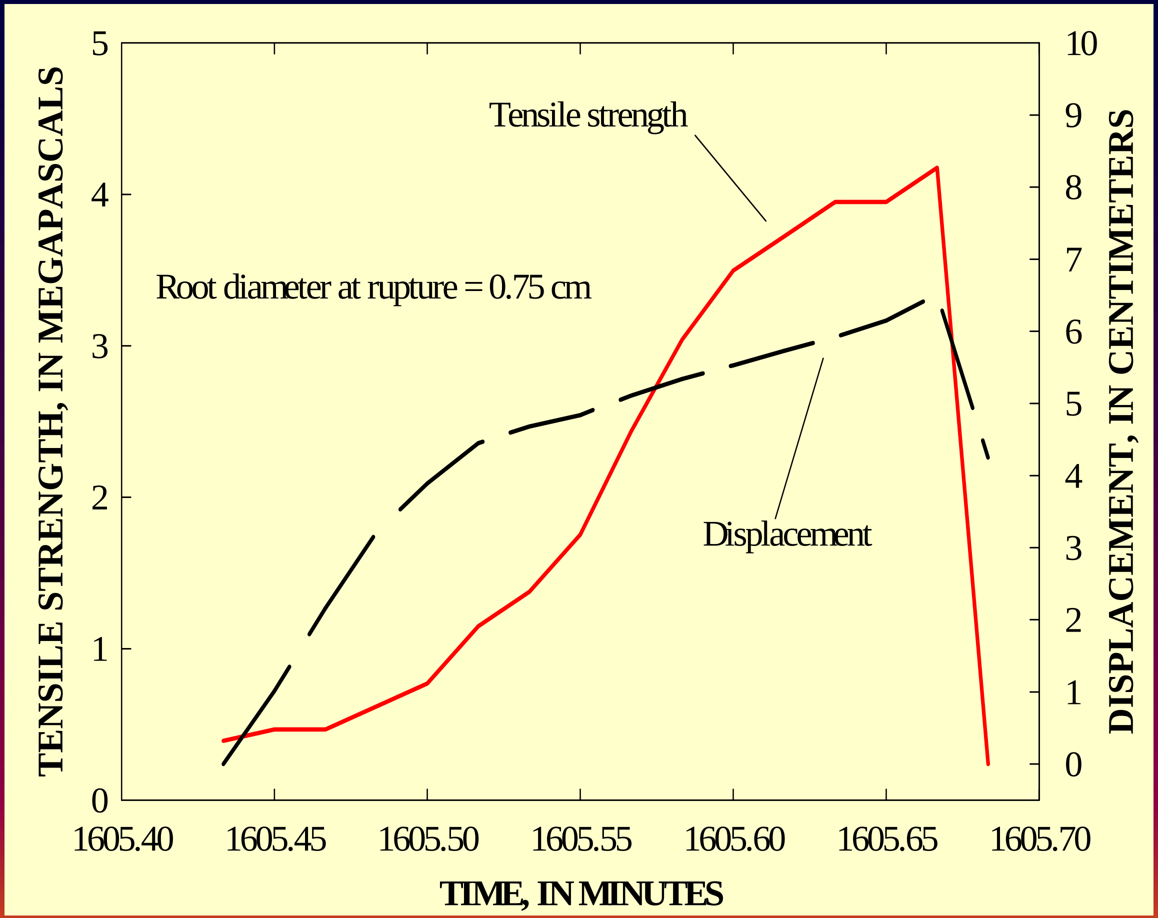
Testing for Root Strength



Root tensile strength tester

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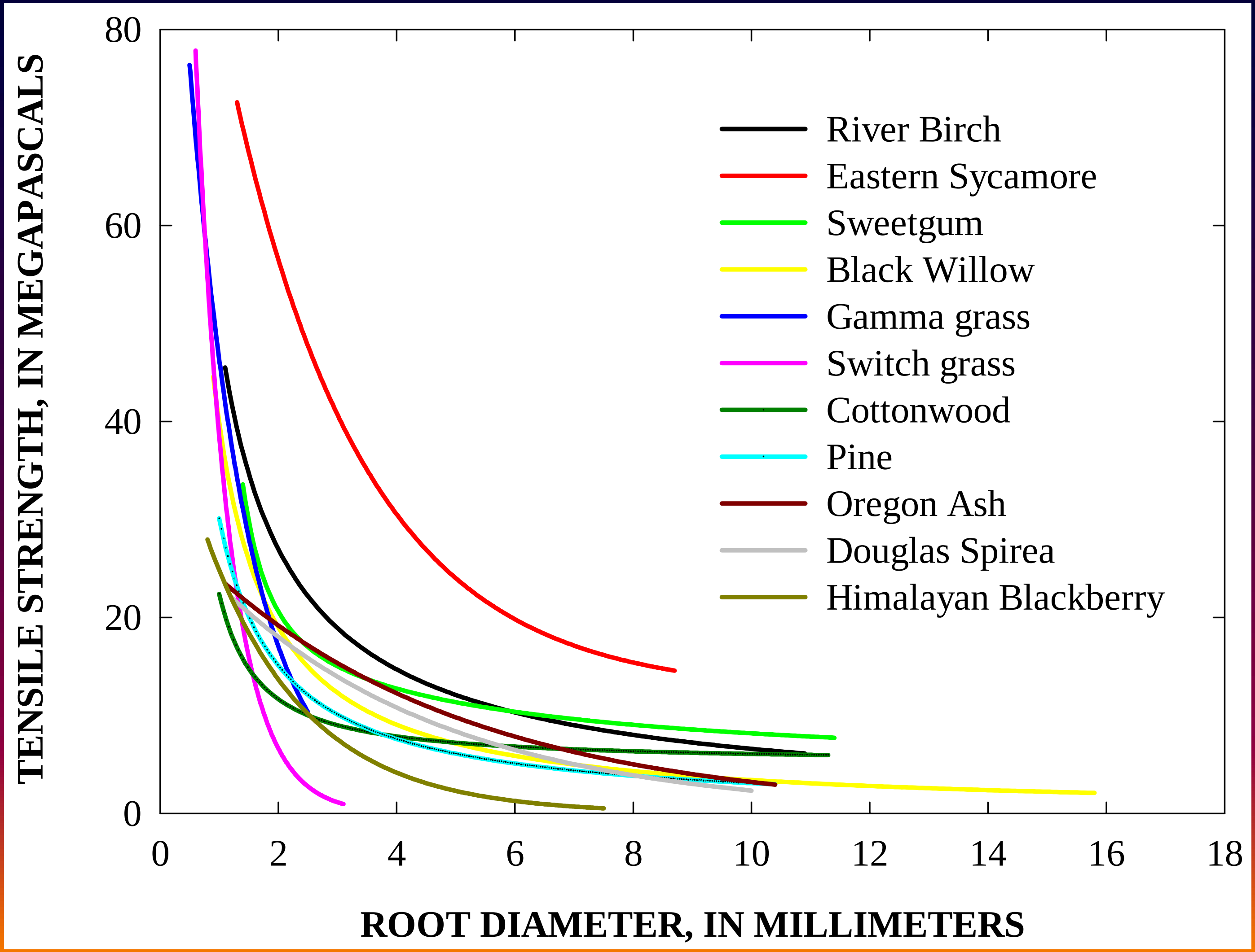
Root Strength: Species Comparison



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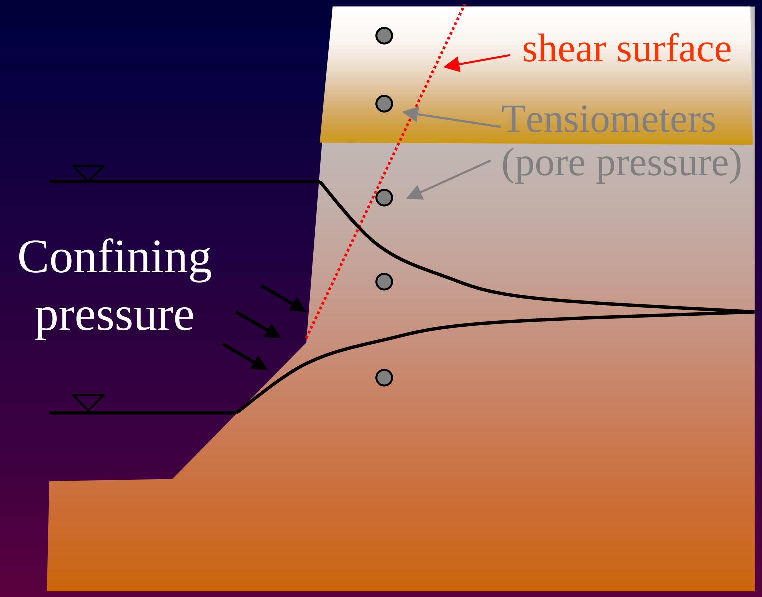
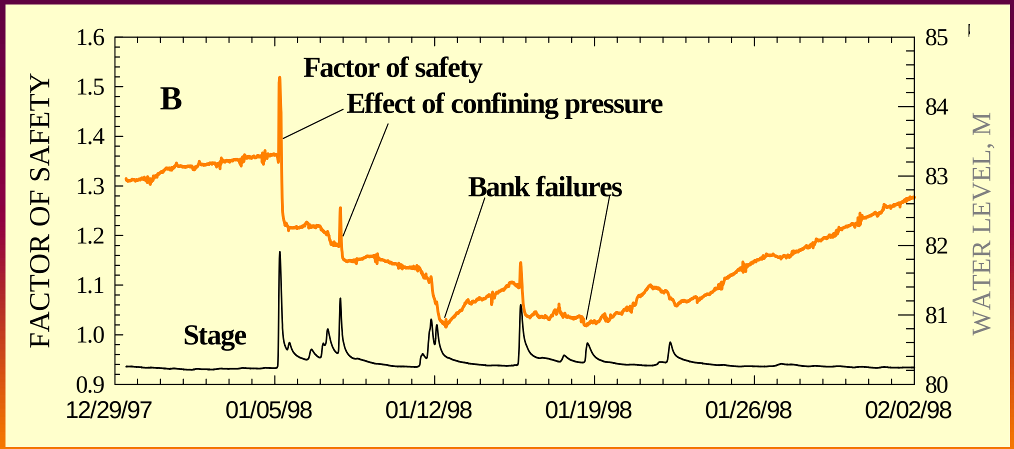
Bank-Stability Model

- 2-D wedge-failure model
- Incorporates both positive and negative pore-water pressures
- Simulates confining pressures from stage
- Incorporates layers of different strength and characteristics
- Calculates toe erosion
- Inputs:
  γ_s, c', ϕ', ϕ^b, h, u_w, τ_c, S





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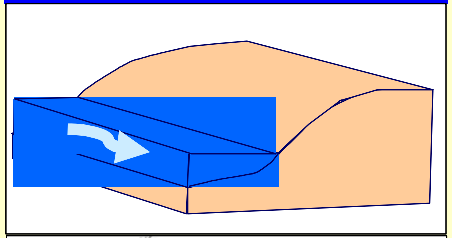
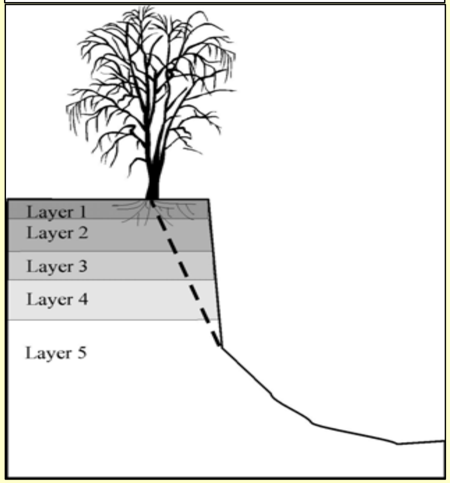
Bank Stability and Toe Erosion Model

Bank Stability and Toe Erosion Model

Static Version 3.4

Latest version available at:
http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/bank.html





Bank Stability Model

The Channel Bank Stability Model is a wedge-based limit equilibrium model that calculates Factor of Safety (*Fs*) for multi-layer river and streambanks. It can easily be adapted to incorporate the effects of geotextiles or other bank stabilization measures that affect soil strength.

The model accounts for the strength of up to five soil layers, the effect of pore-water pressure (both positive and negative (matric suction)) and soil reinforcement and surcharge due to vegetation.

Input the bank coordinates **(Input Geometry)** and run the geometry macro to set up the bank profile, then input your soil types, vegetation cover and water table or pore-water pressures **(Bank Model Step 2** and **Bank Model Data)** to find the Factor of Safety.

The bank is said to be 'stable' if *Fs* is greater than 1.3, to provide a safety margin for uncertain or variable data. Banks with a *Fs* value between 1.0 and 1.3 are said to be 'conditionally stable', i.e. stable but with little safety margin. Slopes with an *Fs* value less than 1.0 are unstable.

This version of the model assumes hydrostatic conditions below the water table, and a linear interpolation of matric suction above the water table (unless the user's own pore-water pressure data are used).

The model can either use estimated input data where no field data are available or as a first pass solution, or can be set to run using your own data. Your own data can be added to white boxes. Don't change values in yellow boxes - they are output.

In addition to this static model there is also a dynamic version that uses a time series of pore-water pressure values to calculate *Fs*.

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Initial Inputs

Input bank geometry and flow conditions

Work through all 3 sections then hit the "Run Bank Geometry Macro" button.

1) Select **EITHER** Option A or Option B for Bank Profile and enter the data in the relevant box- cells in the alternative option are ignored in the simulation and may be left blank if desired.

2) Enter bank material layer thicknesses (if bank is all one material it helps to divide it into several layers).

3) If bank is submerged then select the appropriate channel flow elevation to include confining pressure and calculate erosion amount; otherwise set to an elevation below the bank toe.

You can check to ensure bank profile is correct on either **Toe Model Step 2** or **Bank Model Step 2**.

Option A - Draw a detailed bank profile using the boxes below

○ Option A

Point	Station (m)	Elevation (m)
A		
B		
C		
D		
E		
F		
G		
H		
I		
J		

K - shear emergence: 2.00

Shear surface angle: 50.00

Option B - Enter a bank height and angle, the model will generate a bank profile

◉ Option B

5.0	a) Input bank height (m)
72.0	b) Input bank angle (^{o})
1.0	c) Input bank toe length (m)
25.0	d) Input bank toe angle (^{o})

Either input shear surface angle;

60.0 Input shear surface angle

Or check box and have the model calculate shear surface angle from soil friction angle and bank angle

☐ Calculate shear surface angle from soil friction

30.0 Input mean soil friction angle

Need to know the shear surface angle?

	Input mean bank angle
	Input mean soil friction angle
0.0	**Recommended shear surface angle**

2. Bank layer thickness (m)

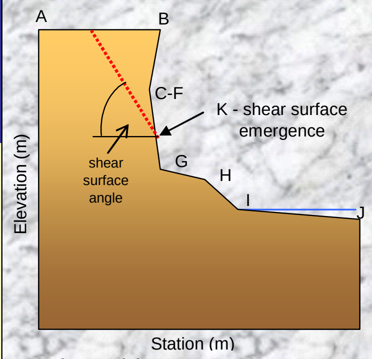
	Bank layer thickness (m)		Elevation of layer base (m)
Layer 1	1.00	Top Layer	4.00
Layer 2	1.00		3.00
Layer 3	1.00		2.00
Layer 4	1.00		1.00
Layer 5	1.00	Bottom Layer	0.00

Parallel layers, starting from point B

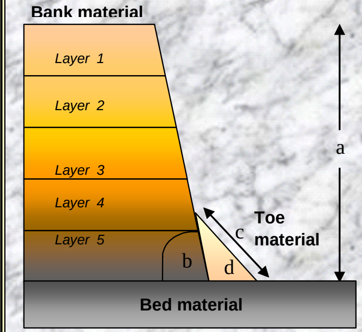
3. Channel flow parameters

2.50	Input elevation of flow (m)
0.003	Input slope of channel (m/m)
20	Input duration of flow (hrs)

Definition of points used in bank profile



A - bank top: place beyond start of shear surface
B - bank edge
C-F - breaks of slope on bank (if no breaks of slope place as intermediary points)
G - top of bank toe
H - break of slope on bank toe (if no break of slope then insert as intermediary point)
I - base of bank toe
J - end point (typically mid point of channel)
K- elevation of point where shear surface emerges on the bank (anywhere between B and G)



Notes:
Shear surface must enter bank top between points A and B.
Bank profile may overhang.
Point K must not be on a horizontal section - the elevation of this point must be unique or an error message will display.

Select which component you wish to use first. You will be automatically redirected to the relevant worksheet after hitting the Run Bank Geometry Macro button

Bank Stability component ▼

Run Bank Geometry Macro

Initial Stability Conditions

Select material types, vegetation cover and water table depth below bank top

(or select "own data" and add values in 'Bank Model Data' worksheet)

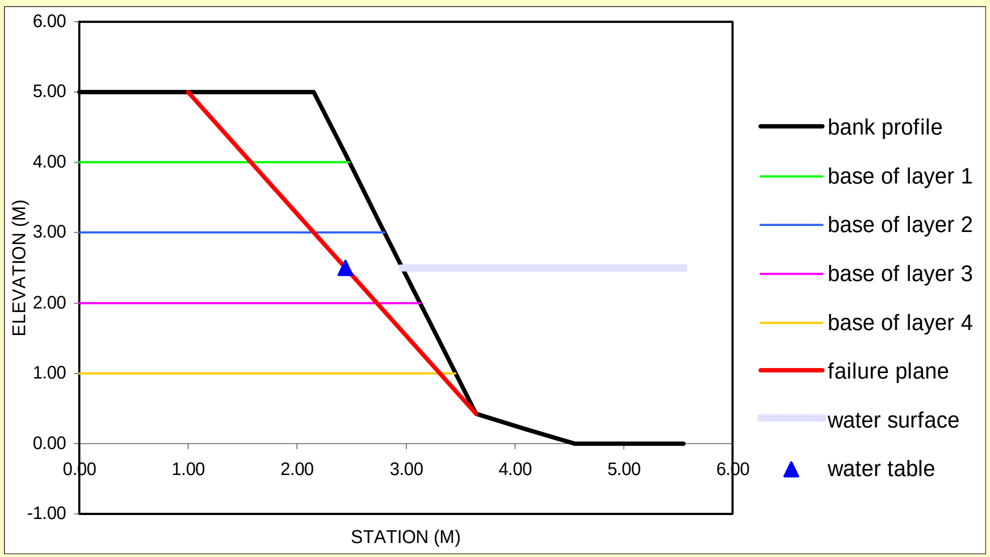
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Gravel	Gravel	Gravel	Gravel	Gravel
Angular sand	Angular sand	Angular sand	Angular sand	Angular sand
Rounded sand	Rounded sand	Rounded sand	Rounded sand	Rounded sand
Silt	Silt	Silt	Silt	Silt
Stiff clay	Stiff clay	Stiff clay	Stiff clay	Stiff clay

Bank top vegetation cover (age): None

Vegetation safety margin: 50

Reach Length (m): 100

Constituent concentration (kg/kg): 0.001



Water table depth (m) below bank top: 2.50

- Use water table (selected)
- Input own pore pressures (kPa)

Own Pore Pressures	kPa	Pore Pressure From Water Table
	Layer 1	-19.62
	Layer 2	-9.81
	Layer 3	0.00
	Layer 4	9.81
	Layer 5	19.62

60.0 Shear surface angle used

Export Coordinates back into model

Factor of Safety

1.28	Conditionally stable

Failure width	1.16	m
Failure volume	264	m^3
Sediment loading	467369	kg
Constituent load	467	kg

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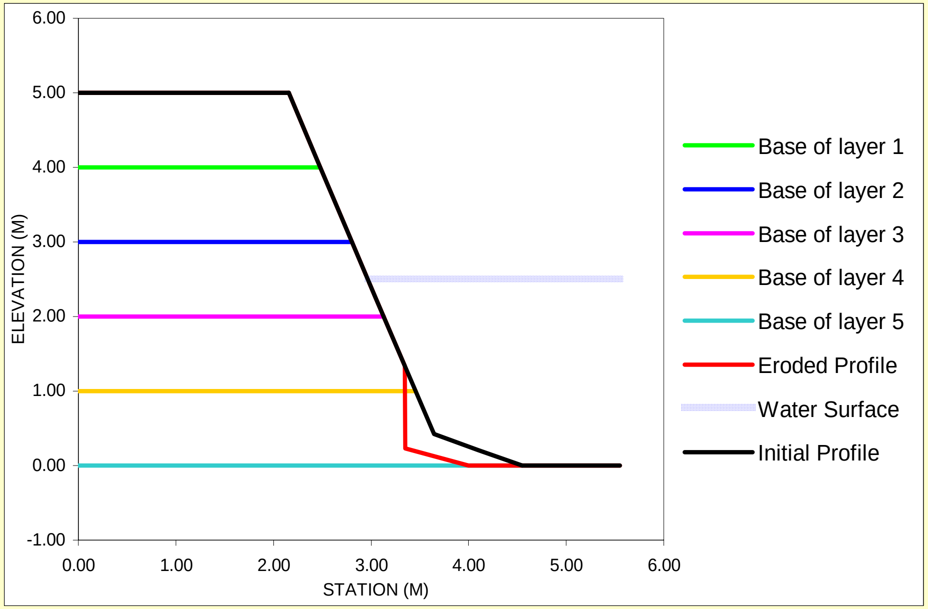
Toe Erosion: 2.5 m flow, 20hrs.

Input bank materials

Specify the erodibility of the different materials. Use the drop down boxes to select material type or select "Enter own data" and add values in the 'Bank Model Data' worksheet. If you select a material, the values shown in the 'Toe Model Data' worksheet will be used. Once you are satisfied that you have completed all necessary inputs, hit the "Run Shear Stress Macro" button (Center Right of this page).

Bank Material					Bank Toe Material	Bed material
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5		
Erodible cohesive	Erodible cohesive	Erodible cohesive	Moderate cohesive	Erodible cohesive	Erodible cohesive	Fixed bed
0.10	0.10	0.10	5.00	0.10	0.10	248.83
0.316	0.316	0.316	0.045	0.316	0.316	0.006



Bank Protection

No protection — Input bank protection

Bank Toe Protection

No protection — Input toe protection

Average applied boundary shear stress	7.76	Pa
Maximum Lateral Retreat	29.07	cm
Mean Eroded Area - Bank	0.06	m^2
Mean Eroded Area - Bank Toe	0.02	m^2
Mean Eroded Area - Bed	0.00	m^2
Mean Eroded Area - Total	0.08	m^2

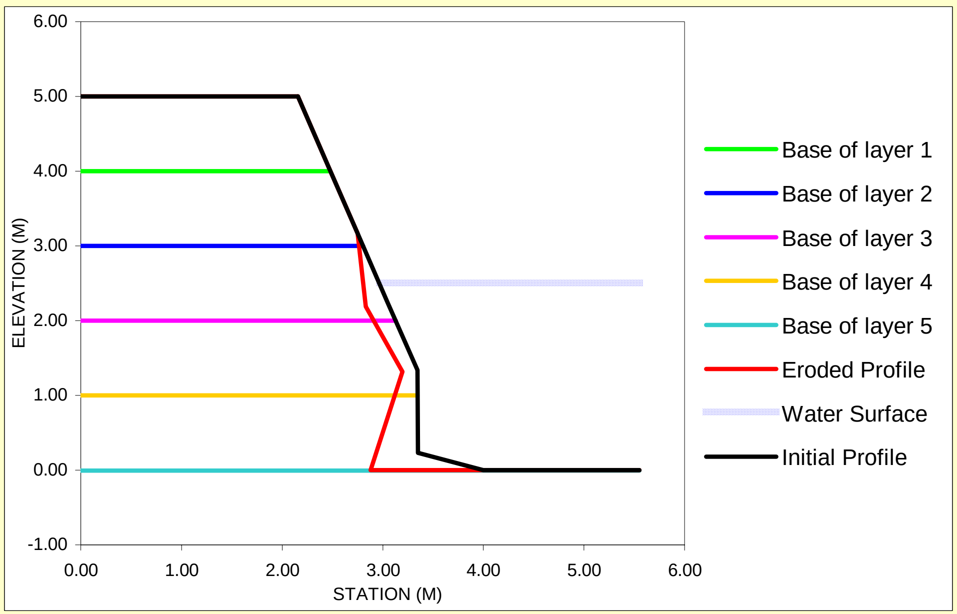
Export Coordinates back into model

Toe Erosion: 2.5 m flow, 20hrs.

Input bank materials

Specify the erodibility of the different materials. Use the drop down boxes to select material type or select "Enter own data" and add values in the 'Bank Model Data' worksheet. If you select a material, the values shown in the 'Toe Model Data' worksheet will be used. Once you are satisfied that you have completed all necessary inputs, hit the "Run Shear Stress Macro" button (Center Right of this page).

Bank Material					Bank Toe Material	Bed material
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5		
Erodible cohesive	Erodible cohesive	Erodible cohesive	Moderate cohesive	Erodible cohesive	Erodible cohesive	Fixed bed
0.10	0.10	0.10	5.00	0.10	0.10	248.83
0.316	0.316	0.316	0.045	0.316	0.316	0.006



Bank Protection

No protection — Input bank protection

Bank Toe Protection

No protection — Input toe protection

Average applied boundary shear stress	22.03	Pa
Maximum Lateral Retreat	46.99	cm
Mean Eroded Area - Bank	0.13	m^2
Mean Eroded Area - Bank Toe	0.00	m^2
Mean Eroded Area - Bed	0.00	m^2
Mean Eroded Area - Total	0.13	m^2

Export Coordinates back into model

Unstable Following Toe Erosion

Select material types, vegetation cover and water table depth below bank top

(or select "own data" and add values in 'Bank Model Data' worksheet)

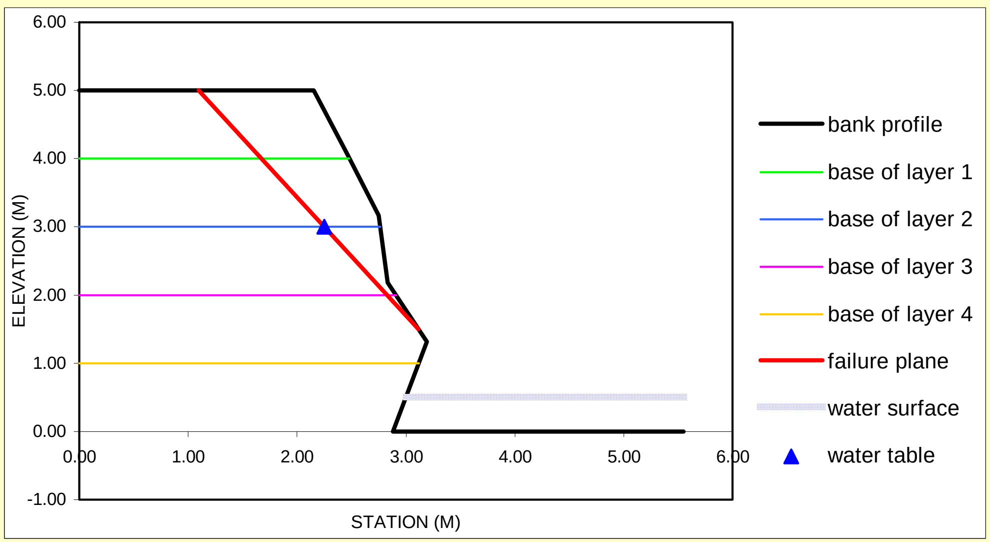
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Gravel Angular sand Rounded sand Silt Stiff clay	Gravel Angular sand Rounded sand Silt Stiff clay	Gravel Angular sand Rounded sand Silt Stiff clay	Gravel Angular sand Rounded sand Silt Stiff clay	Gravel Angular sand Rounded sand Silt Stiff clay

Bank top vegetation cover (age): None

Vegetation safety margin: 50

Reach Length (m): 100

Constituent concentration (kg/kg): 0.001



Water table depth (m) below bank top: 2.00

Use water table

Input own pore pressures (kPa)

Own Pore Pressures	kPa	Pore Pressure From Water Table
	Layer 1	-14.72
	Layer 2	-4.91
	Layer 3	4.91
	Layer 4	14.72
	Layer 5	24.57

60.0 Shear surface angle used

Export Coordinates back into model

Factor of Safety

0.95 Unstable

Failure width	1.06	m
Failure volume	190	m^3
Sediment loading	338446	kg
Constituent load	338	kg

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Addition of Bank-Top Vegetation

Select material types, vegetation cover and water table depth below bank top
(or select "own data" and add values in 'Bank Model Data' worksheet)

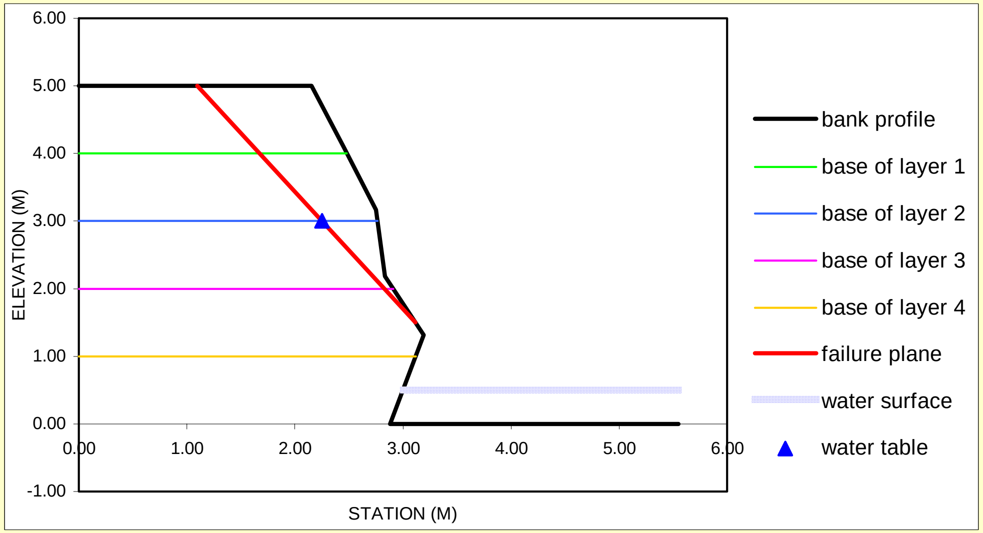
Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Gravel	Gravel	Gravel	Gravel	Gravel
Angular sand	Angular sand	Angular sand	Angular sand	Angular sand
Rounded sand	Rounded sand	Rounded sand	Rounded sand	Rounded sand
Silt	Silt	Silt	Silt	Silt
Stiff clay	Stiff clay	Stiff clay	Stiff clay	Stiff clay

Bank top vegetation cover (age): Sycamore (7 yrs)

Vegetation safety margin: 66

Reach Length (m): 100

Constituent concentration (kg/kg): 0.001



Water table depth (m) below bank top: 2.00

- Use water table
- Input own pore pressures (kPa)

Own Pore Pressures	kPa	Pore Pressure From Water Table
	Layer 1	-14.72
	Layer 2	-4.91
	Layer 3	4.91
	Layer 4	14.72
	Layer 5	24.57

60.0 Shear surface angle used

Export Coordinates back into model

Factor of Safety

1.12	Conditionally stable

Failure width	1.06	m
Failure volume	190	m^3
Sediment loading	344156	kg
Constituent load	344	kg

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